9/3/2004

ACD Photo-multiplier Tube (PMT) Recovery Effort
Review held on 8-30-04
Peer Review Recommendations

Peer Panel Members:

Science Dr. Bob Streitmatter/661	**Structural Analysis** Scott Gordon/542 Cengiz Kunt/Swales
Mechanical Design Armando Morell/544 Rodger Farley/543	**Thermal** Tom McCarthy/545
Glass/Reliability Walt Thomas/302	**Electrical** Jose Florez/560 Art Ruitberg/563

Overview:

The Peer Review was held on 8-30-04 in the Building 30 conference room. The review was well attended by personnel closely affiliated with the project, as well as the review team listed above. The PMT team was praised for their efforts to date and for their grasp of the problem and its solution. Comments and suggestions were solicited from the panel members both during the review and afterwards via e-mail. What follows is a summary of those recommendations sorted by category with the redundant comments eliminated. Also appended are the unedited written inputs by e-mail from the reviewers.

General Recommendations

1. While a majority of the panel members agreed with the chosen solution path (Partially CTE compensated/spring), it was not unanimous. It was strongly suggested to invest time/effort to also mature the Grooved/potted design as a back-up.
2. Given the known flaws in the PMT's, along with the statistical nature of glass failures, can the stated maximum on-orbit failure rate of 3% be achieved? The ACD reliability model has been revised to include an input for the PMT Pf; however, there is no/insufficient data available (to date) to define that number. To mitigate this risk it was recommended that new tubes using the improved process be used. There were reservations regarding the approach to recover use and existing PMT's for flight.

3. Whatever new approach is selected, take the required time to analyze it and understand it before embarking on the development.

Design/Process Recommendations

1. Determine and use Minimum Required Wavy Washer Stiffness in order to minimize thermally induced stresses in the glass tube. Size spring stiffness to maintain a sufficiently high frequency and to keep the vibration induced motions of the PMT sufficiently low.
2. Resolve the parylene migration concern.
3. Resolve the grounding concern with the spring.
4. Perform PMT dimensional measurements, using/based on the lot records from Hammatsu, since the PMT tubes likely would be fabricated as groups and between-tube dimensional variances likely would be related to the fabrication "sequence," i.e., manufacturing lots. You should be able to establish "within lot" variability through these measurements to size the custom delrin parts.
5. If there is room at the base-end of the tube, consider using a "ring" of Kapton insulation between the metal washer and the high voltage leads - Kapton has a very good dielectric constant per thickness and already has been used extensively for spacecraft and space instruments for it outgassing properties.

Analysis Recommendations

1. Address the possibility of local bending (hence tension) at the ends of the glass tube, where load is applied through contact with the delrin inserts. No strain data or stress predictions were presented for these areas. Perform stress analysis of the PMT ends under nominal contact conditions. Also check sensitivity of stresses to non-uniform loading of ends due to tolerance build-up.
2. Develop a compressive stress allowable for the glass tubes. The compressive loading is being applied to a thin walled cylinder so buckling rather than the material compressive strength may be the governing upper bound to stress. The buckling allowable should be checked to ensure that the correct upper bound on compressive load is understood when sizing the mechanical design(s) for preload and final stress state under cold conditions. Thin-wall cylinders are notorious for buckling under compressive stress in either the axial or radial direction There are large de-rating factors on the bulk material properties which must be applied in the cylindrical configuration
3. Check compressive stress peaking near the glass tube end under point loading of the wavy washer. Recommend representing the discrete nature of wavy washer loading on the delrin insert to determine the extent of compressive stress peaking in glass. Combine with results of 1 above.
4. Resolve Glass Compressive Stress Discrepancy between test and analysis and make sure to fully understand the stress state in the glass. Recommend representing stiffening of the spring washer in FEA as it gets flattened out under thermally induced compression. Make hand calculations to check FEA results.

5. Determine and use Minimum Required Compressive Preload in order to minimize stresses induced in the glass tube. Use a Safety Factor of at least 1.25 to unsure no gapping under maximum expected vibration load. Show derivation of minimum preload clearly.
6. Justify use of Housing Strains to screen PMTs. Use FEA to analytically show that when the glass strains are high so are the housing strains.
7. Regarding the notch-potted-debond option: Although it is very low (18 psi), it was not understand why the outer surface of the glass is in tension in the cold condition. Despite a post-meeting discussion of the local-element forces on the glass, it seems that the outer surface would be in longitudinal compression as the RTV contracts. The inner surface might be in tension, in the manner that a loaded beam has tension on the underside surface while having compression on the upper surface. In which case there would be a tension gradient in the radial direction.

Test Recommendations

1. Concern was expressed about the accuracy of strain gauge readings. Discrepancies in stress levels with similar (identical) assemblies have been explained with the differences in the RTV properties, but now having much higher than expected stress on the spring mounted design warrants further investigation and the need to rule out errors in the measurement itself. Suggest instrumenting the qualification PMT's with strain gages on both the aluminum housing and the glass tube and testing under thermal cycling.
2. Strongly recommend reducing the cooling/heating rates to match the expected operating environments. Stress resulting from a through the thickness gradient could easily be a large contributing factor in the type of failures experienced and it needs to be understood and managed. The 20 deg/hour rate should be proved to be a non problem or it needs to be reduced.
3. Conduct a life test program for the redesigned units for the remainder of the project, such that it completes before we launch.

Unedited Individual Review Panel Member Inputs

Armando Morell

* I will like to start by commending the team. The material presented was clear and well organized.

* I agree with the proposed solution. An attempt at reducing the CTE mismatch by strategically combining the aluminum with Delrin plus the introduction of a spring is a more conventional approach, routinely used when mounting optics. This mounting method eliminates the possibility of loading the glass in tension. The concern about contaminating the PMT window during the vacuum deposition step can be reduced or eliminated by masking or covering the window. The other concern we have in moving to this new mounting method results from the potential damage to the PMT lead wires or any of the internal components during vibration. In this new concept the PMT can rattle inside the aluminum tube. I am not particularly worried about this considering the gaps are small and proper stress relieve is planned to protect the lead wires from stress.

* I am growing more concern about having accurate strain gauge readings. Discrepancies in stress levels with similar(identical) assemblies have been explained with the differences in the RTV properties, but now having much higher than expected stress on the spring mounted design warrants further investigation and the need to rule out errors in the measurement itself.

* I am disappointed a more detailed thermal analysis (gradient) has not been performed when the failures have been occurring during cold cycling. I strongly recommend reducing the cooling/heating rates to match the expected operating environments. Stress resulting from a through the thickness gradient could easily be a large contributing factor in the type of failures experienced and it needs to be understood and managed. The 20 deg/hour rate should be proved to be a non problem or it needs to be reduced.

* Last I will like to express my concern in using the tubes that so far survived. Unless our understanding of the failure mode improves there will still be a question on margin and life. I recommend only using new tubes and keeping the ones we already have as spares.

Bob Streitmatter:

Thoughts on the GLAST ACD PMT design peer review.
(1) The "flexibility" (ability to make future alterations in design) of the mechanical-spring approach is evident. However, it is not clear that the chosen mechanical-spring solution is the best answer. Worries include, as per VG 12:

* The inability to match the calculated stresses with the test data
    * The high-voltage proximity to the grounded washer
    * The paralene seep problem
    * Possibility of radial motion in vibration was listed, Although not discussed, a glass tube supported only at both ends is a beam (with annular cross-section), and will likely

have some interesting vibration modes. Re the mechanical-spring solution, I would suggest getting a prototype into vibration testing ASAP.

* Any approach with end supports (only) of the PMT must be very careful about local stresses in the glass at the end points of the tube. That is, minor tube-to-tube variations in size and geometry (e.g. face non-perpendicular to the tube axis, or tube out-of-round) can lead to local point stresses.

(2) Thin-wall cylinders are notorious for buckling under compressive stress in either the axial or radial direction. There are large de-rating factors on the bulk material properties which must be applied in the cylindrical configuration. The Selection Criteria list gives 6000/3000 psi as the limit/goal. I'm not clear what number should be used. Particularly so for a brittle material like glass.

3) Regarding the notch-potted-debond option:

* Although it is very low (18 psi) , I can not understand why the outer surface of the glass is in tension in the cold condition. Despite a post-meeting discussion of the local-element forces on the glass, it seems that the outer surface would be in longitudinal compression as the RTV contracts. The inner surface might be in tension, in the manner that a loaded beam has tension on the underside surface while having compression on the upper surface. In which case there would be a tension gradient in the radial direction. Someone more knowledgeable than I should check this.

(4) In every one of the options, the finite element plots show the highest loads at the ends. (I think.) Not surprising; in cross section there is a right angle at the face. However the calculated stresses will depend very strongly on how the mechanical interfaces to the tube are modeled. This is only to say that any final design should take special notice of modeling the tube ends and whatever interfaces to the ends may exist. Plays into the last bullet in (1) above.

(5) There are enough uncertainties in the mechanical-spring solution, which is basically starting over, that it would seem prudent to advance development of the notch-potted-debond approach to the point where it represents a real and viable backup, if not the primary choice.

Rodger Farley:

Mike and company seem to have a good grasp on the problem, a solution, and the reality of limited resources. The situation is far from ideal, forcing a perhaps too caviler approach. I can't help but think that if primary science requirements require no more than a 3% failure of the PMTs, then how can this mixed bag approach of spares, existing low strain, existing high strain, sprung-mounted and machined-off housings and the like, instill any kind of confidence of meeting the science requirements? There are not enough PMTs to create a good statistical sample, and I just don't know if this 'hope for the best' approach is in line with long term interests. Have all avenues for acquiring new PMTs been investigated? Is it only a matter of money in order to accelerate the vendor's schedule? Does someone else in the US have them sitting on a shelf from a previous project?

Tom McCarthy:

Good review.

My only concern as I stated at the end of our review is to have a life test program for these units underway for the remainder of the project, such that it completes before we launch.

Scott Gordon:

Don't have too many comments. As I stated yesterday, I think the mechanical approach is a good way to go. It gets rid of the variable of the RTV which as seen from testing is difficult to control for both CTE and more importantly Poissons ratio. There is enough variability in the strength of the glass without having to worry about the RTV on top of that. I think either of the mechanical designs is relatively straightforward to implement and it loads up the tubes in a more predictable manner with less variables to worry about.

I would like to see a little more work done to understand the lack of correlation of the wavy spring design with the analysis results. If it is just a bottoming out or stiffening of the spring, then the compressive stresses in the PMT will be bounded by that of the CTE compensation method and there should be no problem. However, if the higher than predicted stresses of the spring design are due to some other mechanism, this should be identified as early as possible.

As far as keeping a parallel path for the grooved housing design, I think this is a good idea simply for the fact that the potted design seems like is a very process/material intensive approach (i.e. selection of release agent and ensuring that the RTV releases over the entire surface area of the tube). If this design is going to be kept as a backup, then it seems beneficial to address some of these issues now rather than later to make sure this really is a viable alternative.

My only real technical comment is about the compressive stress allowable for the glass tubes. I didn't see it mentioned how the compressive strength allowable for the glass was derived. The compressive loading is being applied to a thin walled cylinder so buckling rather than the material compressive strength may be the governing upper bound to stress. The buckling allowable should be checked to ensure that the correct upper bound on compressive load is understood when sizing the mechanical design(s) for preload and final stress state under cold conditions.

Overall, I think the PMT team did an excellent job in defining the problem and coming up with a solution.

Cengiz Kunt:

I think the proposed method of mechanically mounting the PMTs with spring compensation is a good solution. I have the following recommendations to minimize risk of failure.

1. Address Possibility of Local Bending (hence tension) at the ends of the glass tube, where load is applied through contact with the delrin inserts. No strain data or stress predictions were presented for these areas.

Recommend to perform stress analysis of the PMT ends under nominal contact conditions. Also check sensitivity of stresses to non-uniform loading of ends due to tolerance build-up.

2. Check Compressive Stress Peaking near the glass tube end under point loading of the wavy washer.

Recommend to represent the discrete nature of wavy washer loading on the delrin insert to determine the extent of compressive stress peaking in glass. Combine with results of 1 above.

3. Resolve Glass Compressive Stress Discrepancy between test and analysis and make sure to fully understand the stress state in the glass.

Recommend to represent stiffening of the spring washer in FEA as it gets flattened out under thermally induced compression. Make hand calculations to check FEA results.

4. Determine and use Minimum Required Compressive Preload in order to minimize stresses induced in the glass tube. Use a Safety Factor of at least 1.25 to unsure no gapping under maximum expected vibration load. Show derivation of minimum preload clearly.

5. Determine and use Minimum Required Wavy Washer Stiffness in order to minimize thermally induced stresses in the glass tube. Size spring stiffness to maintain a sufficiently high frequency and to keep the vibration induced motions of the PMT sufficiently low.

6. Justify use of Housing Strains to screen PMTs. Use FEA to analytically show that when the glass strains are high so are the housing strains.

Walt Thomas:

1. Another panel member commented on this and I fully concur:

The Team has received pressure from the program to "rush" to a decision on which course to take, to minimize the schedule impact. However, it would be prudent for the Team to assess all issues regarding the proposed solutions before deciding on the final path(s). To do otherwise may set the schedule back even worse if some other "unknown" or unforeseen problem or issue appears - as a result of a hasty decision. Do the "good engineering" up front.

2. The "mechanical" solutions (partially compensated, "spring washer") get away from the process inconsistencies involving the potting materials. However, the Team must be sure they have ascertained all the potential issues/problems with the mechanical solutions before proceeding.

3. One pressing issue regarding the "pre-loaded spring washer" solution is the lack of correspondence between the actual measured stresses and the "modeled" stresses on the glass tube. This needs to be resolved before proceeding - to avert another potential problem/issue that would adversely impact schedule.

4. There was limited discussion of instrumenting a (PMT) tube with strain gages on both the aluminum housing and the glass tube and testing under thermal cycling. This MUST be done BEFORE PROCEEDING. One must ascertain the actual stresses on the glass tube in the "new" mechanical configuration(s). This also may/should confirm the finite element analyses model(s), which likely have been inaccurate for the past configurations (that is, the stresses predicted may not have accurately the actual conditions seen by the glass tube.)

4. I'll reiterate two "process" suggestions made on Monday:

a. Individual PMTs must be measured for dimensions before the nylon washers are fabricated. Perform these measurements, using/based on the lot records from Hammatsu, since the PMT tubes likely would be fabricated as groups and between-tube dimensional variances likely would be related to the fabrication "sequence," i.e., manufacturing lots. You should be able to establish "within lot" variability through these measurements (analysis of variance, based on your measured dimensions). This then will "dictate" the numbers of individual PMTs that will/would have to be measured. Based on those (PMT) measured dimensions and the (sampling) measured dimensions of the aluminum housings, one then can determine the expected variances that will need to be accounted in sizing the nylon washers. For variances that indicate "several groups," appropriate sized washers would be fabricated and "binned." Based on the measured dimensions (from the first part of this para.) the operators then selected the appropriately sized washer(s) from the various "bins."

b. It may be too late to consider, but locating the spring washer at the "window" end of the tube would get around the high electrical potentials at the base-end of the tube. Since the tube is rigid, it would simply transfer the force from the threaded "screw" to the other end of the tube.

5. New suggestion: If there is "room" at the base-end of the tube, consider using a "ring" of Kapton insulation between the metal washer and the high voltage leads - Kapton has a very good dielectric constant per thickness and already has been used extensively for spacecraft and space instruments for it outgassing properties.

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////////////////////   Al housing
----------             Kapton "ring"

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               HV lead(s)


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6. CAUTION: Note that the base-end of the tube is the more fragile end. It consists of a glass-to-metal seal assembly (to pass the signal and power leads) fused onto the tube body; photo-elastic evaluation of the base end indicated that the residual stresses from the glass-to-glass fusing are minimal and the metal-glass residual stresses are essentially nil (at room temperature). Also, a "tubulation" is located on the base end, that is used to evaluate and back-fill the PMT assembly. This "protrusion" is susceptible to damage and subsequent cracking if mishandled.

7. Correction to several comments I heard stated during the review, to the effect that "...we don't understand why the glass (PMTs) is failing."

We do understand why the glass tubes are failing. (a) They have flaws on their outside surfaces, such that the number and severity of the flaws are different for different tubes. (b) When a (tensile) stress is imposed on the glass tube exceeding its practical strength, the glass fractures - resulting in a crack. (c) Fracture surfaces examined to date all indicated that the cracks initially propagated slowly (large mirror surfaces/areas) and then accelerated after having moved either several millimeters longitudinally or nearly across the tubes' wall thickness. (d) Fact (c) indicates that the stress(es) causing glass cracking were relatively "constant" (as opposed to being an impact stress). (e) In some cases (three), we were able to determine the fracture stress at the fracture origins as being ~ 50 - 80 MPa. (f) As the macroscopic stresses imposed on the tubes during thermal cycling were considerably lower, this indicates the "stress magnification" effect(s) of the pre-existing flaws and/or the ambient (water-vapor containing) environment. (g) Failures occurring during the hot-to-cold cycle(s) are consistent with tensile stresses being imposed on the outside tube walls.

A more accurate re-statement of the above comments would be: "We do not understand the stresses being imposed on the glass tubes during thermal cycle testing."

Note that after C. He et al. presented inspection findings to Hammatsu (mid-May), the vendor has improved his PMT manufacturing process to substantially reduce the number and severity of outside surface flaws and entirely eliminate the "inside scorelines" (based on receiving inspections in late July of a few tens of tubes).

8. At this point, we still are not in a position to predict the reliability of the PMTs to be used in the flight instrument. The ACD reliability model has been revised to include an input for the PMT Pf; however, there is no/insufficient data available (to date) to define that number.

9. I caution the program about continuing to refer to or use the previous strength testing data [they refer to it as the "Weibull data"] for the existing problem. It is NOT APPLICABLE and misleading. (Inside vs. outside flaws, different environmental conditions, different stress states).

Jose Florez:

I have the same two recommendations I stated at the review:

1) Whatever new approach is selected, take the required time to analyze it and understand it before embarking on the development. I understand that schedule pressures are great, but this is going to be the 3rd attempt at building the PMTs. If we don't take the time to insure we do it right now, where are we going to find more time to fix it later? From the review it was obvious that the original approach was not clearly understood until after the fact.

2) Given the tight schedule and the experience with the PMTs up until now, it would make sense to select two approaches and run them thru qual testing in parallel in order to mitigate risk.